Exclusive photo- and electroproduction of excited light vector mesons via holographic model

Emmanuel Gräve de Oliveira

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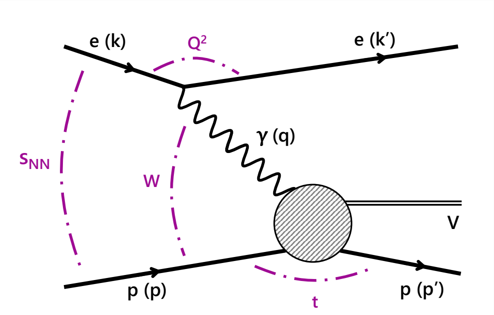
Universidade Federal de Santa Catarina
In collaboration with Cheryl Henkels, Haimon Trebien, Roman Pasechnik

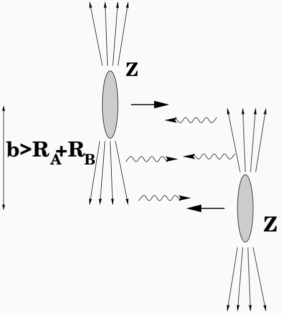
Outline

- dipole approach to photoproduction
- light vector meson wavefunction
- γp results
- nuclear target and shadowing
- γA result

Electroproduction and Photoproduction

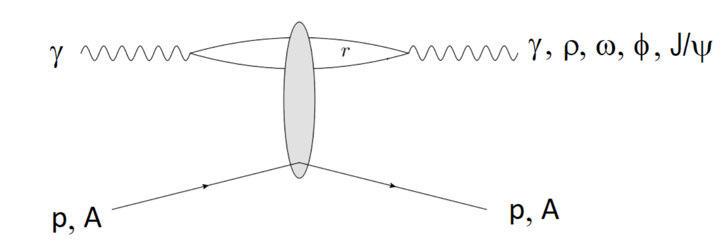


Real and virtual photons exchange for HERA and EIC.



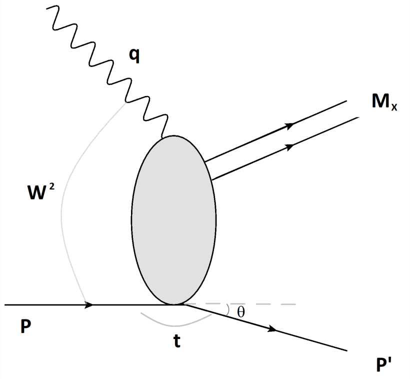
Interaction intermediate by real photons at LHC.

γp final states



- Light vector mesons: ρ, ω e ϕ and excited states.
- This process does not have a hard scale, i.e., Q^2 is small.
- Exclusive production: the target does not break.

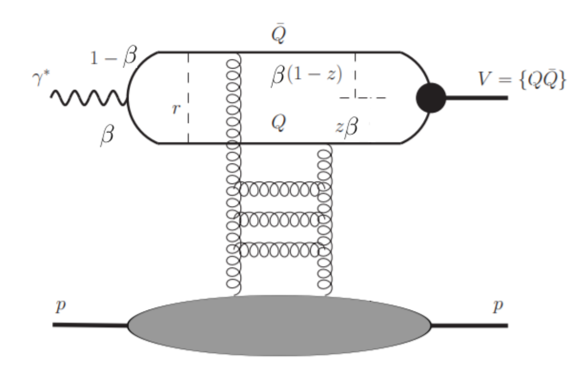
Kinematics



$$W^2 = (P+q)^2\,, \quad t = (P'-P)^2 = -|\Delta|^2\,, \quad x = \frac{M_X^2 + Q^2}{W^2 + Q^2}\,.$$

t–differential cross section

$$\frac{d\sigma^{\gamma p \to Vp}}{dt}(W,t) = \frac{1}{16\pi}\left|\mathcal{A}^{\gamma p \to Vp}(W,t)\right|^2.$$



The product of the subprocesses gives us the total amplitude

$$\mathcal{A}^{\gamma p \to Vp} = 2i \int d^2\mathrm{r} \int_0^1 d\beta \int d^2\mathrm{b} \Psi_V(r,\beta)\Psi_\gamma(r,\beta) \times e^{-i[\mathrm{b}-(1-2\beta)\mathrm{r}/2]\cdot\Delta} N(x,\mathrm{r},\mathrm{b}),$$

Dipole cross section

Optical theorem: the imaginary part of the elastic dipole amplitude ($\Delta \approx 0$) with the dipole cross section

$$\begin{aligned}\sigma_{q\bar{q}} &= \mathrm{Im}\mathcal{A}_{q\bar{q}}(x, \mathrm{r}, \Delta \approx 0) \\ &= \int d^2\mathrm{b}\, 2[1 - \mathrm{Re}S(x, \mathrm{r}, \mathrm{b})]\,.\end{aligned}$$

We define the partial dipole scattering amplitude

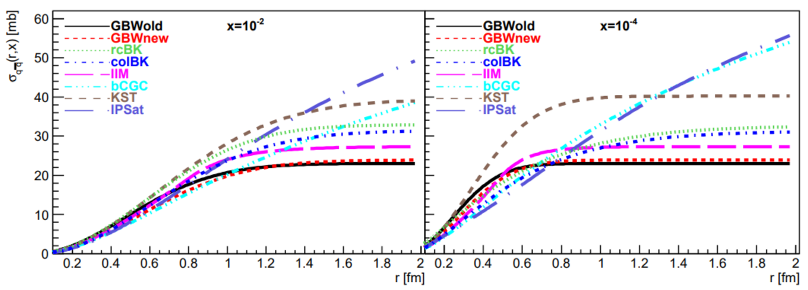
$$\frac{d\sigma_{q\bar{q}}}{d^2\mathbf{b}} = 2[1 - \mathrm{Re}S(x, \mathrm{r}, \mathrm{b})] = 2N(x, \mathbf{r}, \mathbf{b})\,.$$

Then we work with the b–dependent dipole cross section.

Dipole cross section fits

Two main considerations are taken:

- Color transparency: $r \to 0$.
- Saturation: $r \gg 0$.



[Cepila, Nemchik, Krelina, Pasechnik, EPJ C 79, 495 (2019)]

Discrepancy at large $r \to$ light vector meson opportunity.

bSat model

bSat model was fitted to HERA F_2 data with $Q^2 > 0.25$ GeV^2 [Kowalski and Teaney Phys. Rev. D 68, 114005, 2003]

$$N(x, \mathrm{r}, \mathrm{b}) = 1 - \exp\left(-\frac{\pi^2}{2N_c} r^2 \alpha_S(\mu^2) x g(x, \mu^2) T(b)\right) ,$$

Takes into account some $\ln Q^2$ contributions.

Here we use the PDF CT14LO for the gluon distribution, with scale $\mu^2 = 4/r^2 + \mu_0^2$, and $\mu_0^2 = 1.17$ GeV^2) [Kowalski, Motyka and Watt, Phys. Rev. D 74 074016, 2006].

The b profile used is: rho

$$T(b) = \frac{1}{2\pi B_G} e^{-b^2/2B_G}$$

with $B_G = 4.25$ GeV^2 fitted to J/ψ electroproduction.

bCGC model

bCGC model was fitted to HERA F_2 data with $Q^2 > 0.75$ GeV^2 [Rezaeian and Schmidt, Phys. Rev. D 88, 074016 (2013)].

It interpolates solutions to the Balitsky-Fadin-Kuraev-Lipatov (BFKL) and the Balitsky-Kovchegov (BK) equations:

$$N(x, \mathrm{r}, \mathrm{b}) = \begin{cases} N_0 \left(\frac{r\, Q_s}{2}\right)^{2[\gamma_s + (1/(\eta \Lambda Y)) \ln(2/rQ_s)]}, & rQ_s \leq 2 \\ 1 - e^{-A \ln^2 (B\, r\, Q_s)}, & rQ_s > 2 \end{cases},$$

in which $Y = \ln(1/x)$, and

$$Q_s \equiv Q_s(x, b) = \left(\frac{x_0}{x}\right)^{\Lambda/2} \left[\exp\left(-\frac{b^2}{2B_{\mathrm{CGC}}}\right)\right]^{1/(2\gamma_s)},$$

is the saturation scale with a dependence in the impact parameter with $B_{\mathrm{CGC}} = 5.5$ GeV^{-2} fitted to J/ψ electroproduction.

Photon wave function $\Psi^{(\mu,\bar{\mu})}_{\gamma_{T,L}}$

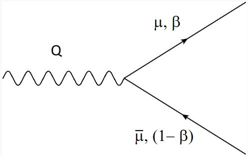
The photon wave function can be calculated perturbatively $\Psi^{(\mu,\bar{\mu})}_{\gamma_{T,L}}$. In terms of the light-cone variables we have

$$\Psi^{(\mu,\bar{\mu})}_{\gamma_{T,L}}(r,\beta;Q^2) = \frac{\sqrt{N_c \alpha_{em}}}{2\pi} Z_q \chi_q^{\mu\,\dagger} \hat{\mathcal{O}}_{T,L} \tilde{\chi}_{\bar{q}}^{\mu} K_0(\epsilon r)\,,$$

where $\epsilon^2 = \beta(1-\beta)Q^2 + m_q^2$ and

$$\hat{\mathcal{O}}_T = m_q \vec{\sigma}\cdot\vec{e}_\gamma + i(1-2\beta)(\vec{\sigma}\cdot\vec{n})(\vec{e}_\gamma\cdot\vec{\nabla}_r) + (\vec{n}\times\vec{e}_\gamma)\vec{\nabla}_r\,,$$

$$\hat{\mathcal{O}}_L = 2Q\beta(1-\beta)\vec{\sigma}\cdot\vec{n}, \quad \vec{\sigma} = (\sigma_x,\sigma_y,\sigma_z), \quad \vec{\nabla}_r \equiv \partial/\partial\vec{r}\,.$$



Nikolaev and Zakharov, Z. Phys. C49, 607 (1991).

Meson wave function

The helicity dependent meson wavefunctions can be written in terms of the scalar wavefunction $\phi_{T,L}(\beta,\zeta)$ [Forshaw and Sandapen, Phys. Rev. Lett. 109, 081601 (2012)].

Longitudinally polarized mesons:

$$\Psi^{V,L}_{h,\bar{h}}(\beta,r) = \sqrt{\frac{1}{4\pi}}\delta_{h,-\bar{h}}\frac{1}{M_V\beta(1-\beta)}[\beta(1-\beta)M_V^2 + m_q^2 - \partial_r/r + \partial_r^2]\phi_L(\beta,r).$$

Transversely polarized mesons

$$\Psi^{V,T(\gamma=\pm)}_{h,\bar{h}}(\beta,r) = \pm\sqrt{\frac{1}{4\pi}}\frac{\sqrt{2}}{\beta(1-\beta)} \times [ie^{\pm i\theta_r}(\beta\delta_{h_\pm,\bar{h}_\mp} - (1-\beta)\delta_{h_\mp,\bar{h}_\pm})\partial_r + m_q\delta_{h_\pm,\bar{h}_\pm}]\phi_T(\beta,r)\,.$$

Normalization condition

$$\sum_{h,\bar{h}}\int d^2r d\beta \mid \Psi^{\lambda}_{h,\bar{h}} \mid^2 = 1\,.$$

Holographic meson wave function

There is a correspondence between string states in anti-de Sitter space (AdS) and conformal field theories (CFT) in Minkowski spacetime.

Assuming that the correspondence holds for QCD and using a semi-classical approach to AdS [Brodsky, Teramond, Phys.Rev.Lett. 102], one has

$$\phi(\beta, \zeta, \varphi) = \frac{\Phi(\zeta)}{\sqrt{2\pi\zeta}} f(\beta) e^{iL\varphi}$$

in which $\zeta = \sqrt{\beta(1-\beta)}r$ and $f(\beta) \sim \sqrt{\beta(1-\beta)}$

The function $\Phi(\zeta)$ satisfies a (fully relativistic) Schrödinger type equation

$$\left(-\frac{d^2}{d\zeta^2} - \frac{1-4L^2}{4\zeta^2} + U(\zeta)\right)\Phi(\zeta) = M^2\Phi(\zeta)$$

where $U(\zeta)$ is the effective confining potential.

The soft-wall model

The soft-wall potential is given by

$$U(\zeta) = \kappa^4\zeta^2 + 2\kappa^2(J-1)\,.$$

From which we extract the eigenvalues of the previous Schrödinger eq.

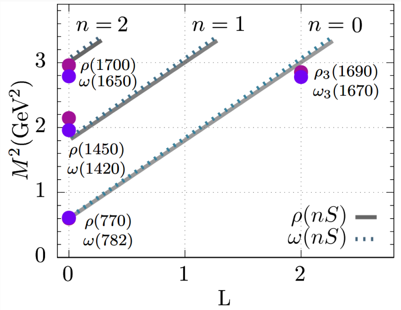
$$M^2 = 4\kappa^2(n + \frac{J}{2} + \frac{L}{2})\,.$$

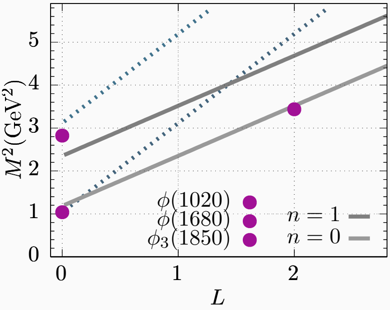
The dynamical part has an analytical solution

$$\Phi_{n,L}(\beta,\zeta) = \kappa^{1+L}\sqrt{\frac{2n!}{(n+L)!}}\zeta^{1/2+L}\exp\left(\frac{-\kappa^2\zeta^2}{2}\right)L_n^L(\kappa^2\zeta^2)\,,$$

where $L_n^L(\kappa^2\zeta^2)$ are the Laguerre polynomials. This approach enable us to calculate the meson wave function not only for the fundamental state, but also for excited ones.

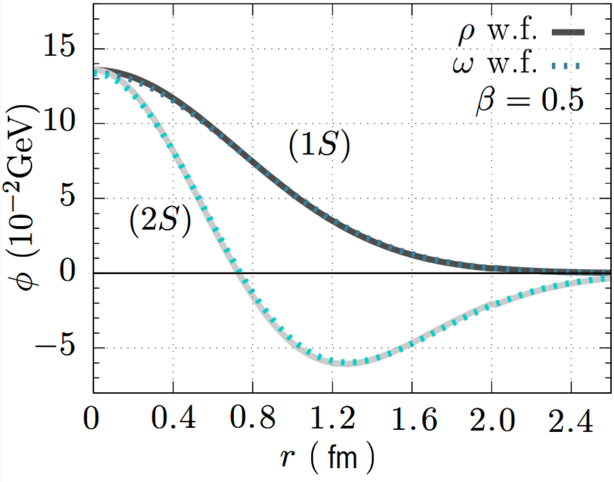
For each family: $\kappa = M_{n=0}/\sqrt{2}$





A varying κ is capable of describing the spectroscopy of ρ and ω and its excited states for $L=0$.

Meson wave function



ρ, ω ground and excited state wave function, the latter with a node.

Including the mass of the quarks

Using the ansatz proposed by Brodsky and Téramond, for massive quarks we substitute the M for the invariant $M_{q\bar{q}}$,

$$M^2 = \frac{\mathbf{k}_\perp^2}{\beta(1-\beta)} \to M_{q\bar{q}}^2 = \frac{\mathbf{k}_\perp^2}{\beta(1-\beta)} + \frac{m_q^2}{\beta} + \frac{m_{\bar{q}}^2}{1-\beta}\,,$$

Then, the meson wave function modifies to

$$\phi_{n,L}(\beta,\zeta) \sim \sqrt{\beta(1-\beta)}\, e^{\frac{1}{2\kappa^2}\left(\frac{m_q^2}{\beta}+\frac{m_q^2}{1-\beta}\right)} \zeta^2 e^{-\frac{1}{2}\kappa^2\zeta^2} L_n^L(\kappa^2\zeta^2)\,.$$

Here, we consider $m_{u,d} = 0.14$ GeV and $m_s = 0.35$ GeV (not bare masses).

For the real part, from dispersion relations:

$$\mathcal{A}^{\gamma p} \to \mathcal{A}^{\gamma p}\left(1 - i\frac{\pi\lambda}{2}\right), \quad \text{com} \quad \lambda = \frac{\partial \ln \mathcal{A}^{\gamma p}}{\partial \ln(1/x)}\,.$$

The two gluons do not have the same x, we factor the skewedness correction [Shuvaev, Golec-Biernat, Martin and Ryskin, Phys. Rev. D60, 014015 (1999)]:

$$R_g(\lambda) = \frac{2^{2\lambda+3}}{\sqrt{\pi}}\frac{\Gamma(\lambda+5/2)}{\Gamma(\lambda+4)}\,.$$

Differential in t cross section is calculated

$$\mathcal{A}^{\gamma p}(x,t) = i\int d^2\mathrm{r}\int_0^1 d\beta\int d^2\mathrm{b}\Psi_V(r,\beta)\Psi_\gamma(r,\beta)\mathrm{e}^{-i[\mathrm{b}-(1-2\beta)\mathrm{r}/2]\cdot\Delta}\frac{d\sigma_{q\bar{q}}}{d^2\mathrm{b}}\,.$$

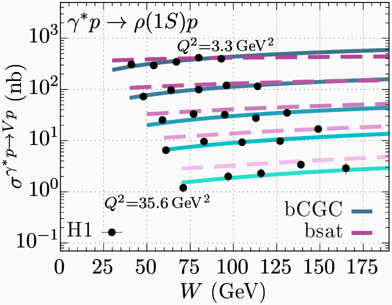
To obtain the integrated cross section, is enough to use the limit of low t:

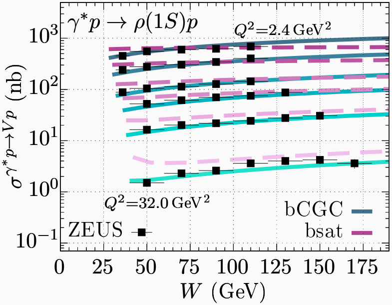
$$\mathcal{A}^{\gamma p\to Vp}(W,t) \approx e^{-B_s|t|/2}\mathcal{A}^{\gamma p\to Vp}(W,t\approx 0)\,.$$

B_s is fitted to the data and give us back the exponential dependence for low t [Forshaw, Sandapen and Shaw, Phys. Rev. D 69, 094013 (2004)]:

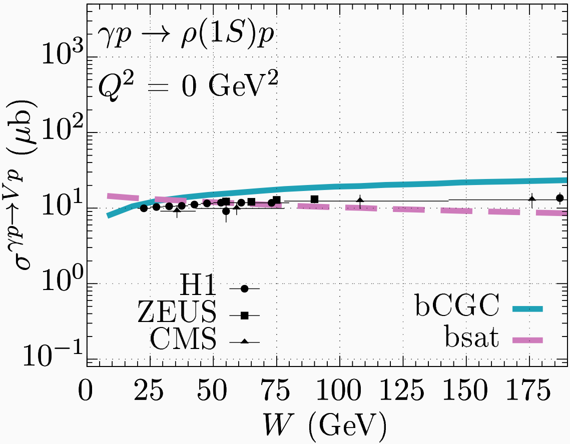
$$B_s = N\left[14.0\left(\frac{1\mathrm{GeV}^2}{Q^2+M_V^2}\right)^{0.2}+1\right]\,.$$

with $N = 0.55$ GeV^{-2}.

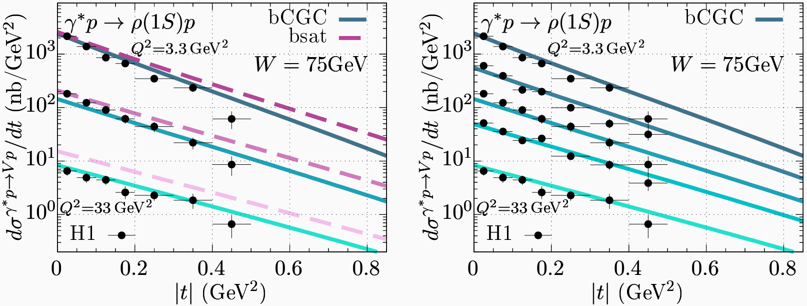




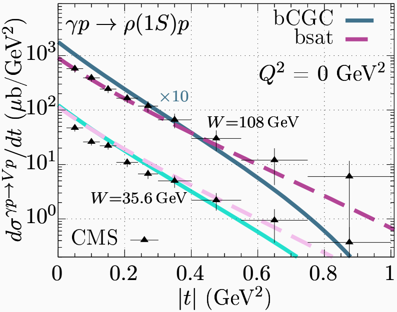
Total cross section for $\rho(1S)$ electroproduction as a function of W obtained by using the holographic wave function, together with the bCGC and bsat dipole models. On the left, from top to bottom, we have Q^2 = 3.3, 6.6, 11.9, 19.5 and 35.6 GeV^2 and on the right, from top to bottom, Q^2 = 2.4, 3.7, 6.0, 8.3, 13.5 and 32.0 GeV^2, respectively.

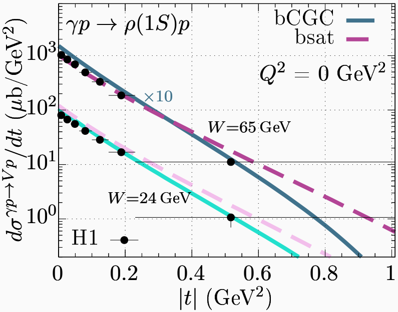


Total cross section for the $\rho(1S)$ photoproduction as a function of the center of mass energy W.

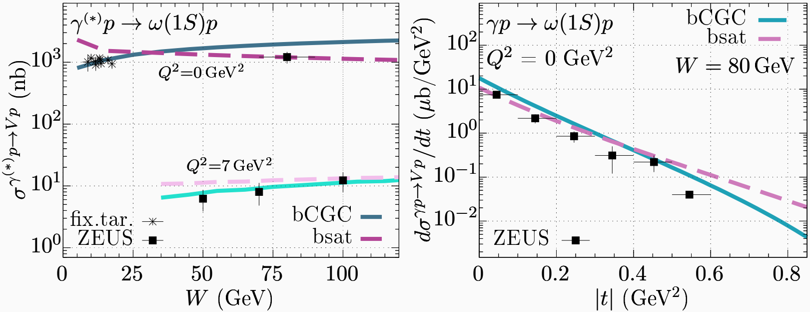


The left panel shows three distinct values of Q^2 (from top to bottom, $Q^2 =$ 3.3, 11.5 and 33.0 GeV^2, respectively). The right panel presents the curves obtained only with the bCGC model and compared to the H1 data for five different Q^2 values (from top to bottom, $Q^2 =$ 3.3, 6.6, 11.5, 17.4 and 33.0 GeV^2, respectively).

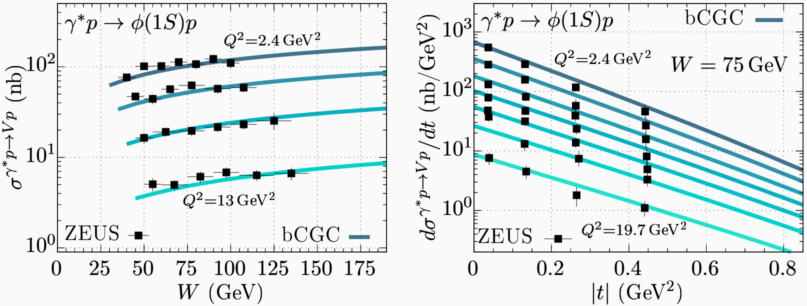




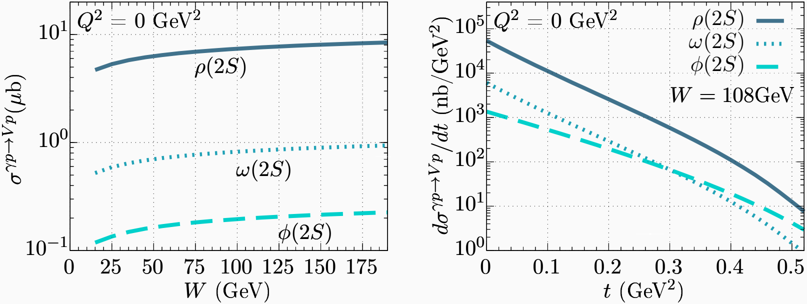
Differential cross section of $\rho(1S)$ photoproduction as a function of the momentum transfer squared $|t|$ obtained with the bCGC and bsat dipole models for different values of W and compared to the corresponding data from the CMS collaboration (left panel) and to those from the H1 collaboration (right panel).



On the left panel, the total cross section is shown as a function of W for $Q^2 = 0$ GeV^2 (darker curve) and $Q^2 = 7$ GeV^2. On the right panel, the differential cross section is shown as a function of momentum transfer squared $|t|$ for $W = 80$ GeV in comparison to the ZEUS.

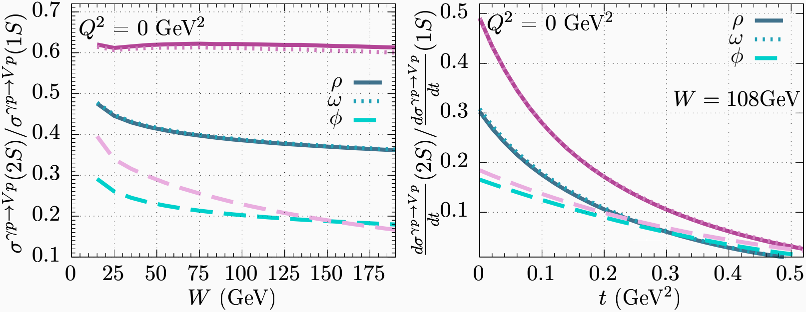


Results for the $\phi(1S)$ electroproduction cross sections compared with the ZEUS data. On the left panel, from top to bottom, $Q^2 = 2.4$, 3.8, 6.5 and 13.0 GeV^2. On the right panel, the differential cross section versus data points for seven different values of Q^2 ($Q^2 = 2.4$, 3.6, 5.2, 6.9, 9.2, 12.6 and 19.7 GeV^2).



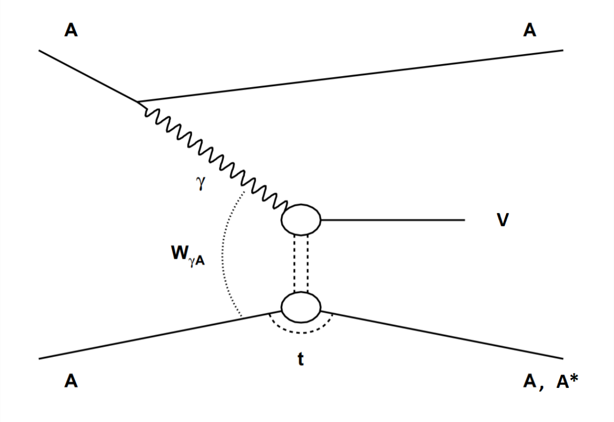
Predictions for the total photoproduction cross section (on the left) and the differential cross section (on the right) for $\rho(2S)$, $\omega(2S)$ e $\phi(2S)$.

Predictions for the ratio between excited and fundamental states



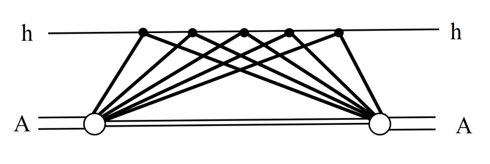
We also make some predictions considering the ratio between the exclusive production of excited states and fundamental ones for the total (left) and differential (right) cross sections.

[Exclusive photo- and electroproduction of excited light vector mesons via holographic model. Henkels, E. G. O., Pasechnik, Trebien, arXiv 2207.13756 (submitted to EPJ C)]

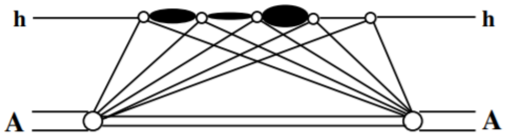


In ultraperipheral collisions, the vector mesons can be produced coherently, which is when the target remains intact. In instances, where the does not remain intact, the production is incoherent.

Coherent amplitude — Glauber–Gribov



Glauber model - only elastic scattering



Gribov correction: adds diffractive intermediate states

Coherent cross section - Dipole model

Glauber–Gribov cross section with the dipole model for large nucleus:

$$\sigma^{\gamma A \to VA} = \int d^2b \Big| \int d\beta d^2 r \Psi_V^\dagger \Psi_\gamma \left[1 - \exp\left(-\frac{1}{2}\sigma_{q\bar{q}}(x,r) T_A(b)\right)\right] \Big|^2$$

The thickness function,

$$T_A(b) = \int_{-\infty}^{+\infty} dz\, \rho_A(b,z)\,, \qquad \frac{1}{A}\int d^2b\, T_A(b) = 1$$

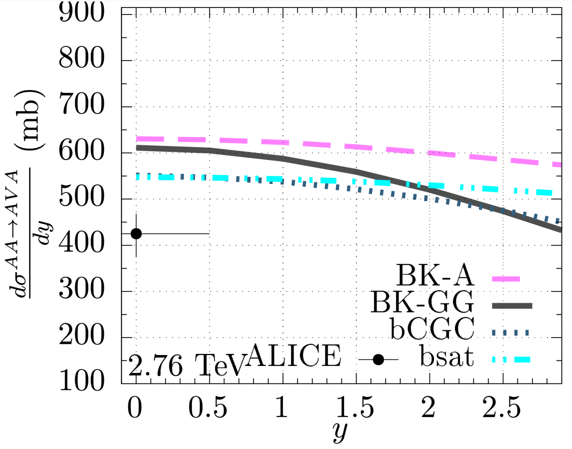
is given by the z spatial coordinate integral of the Woods-Saxon distribution for nuclear density[Woods and Saxon, Phys. Rev. 95, 577 (1954)]:

$$\rho_A(b,z) = \frac{N_A}{1 + \exp\left[\frac{r(b,z)-c}{\delta}\right]}\,, \qquad r(b,z) = \sqrt{b^2 + z^2}\,,$$

The parameters for the Pb nuclei are $c = 6.62$ fm and $\delta = 0.546$ fm, while N_A is a normalization term [Euteneuer, Friedrich, and Vogler, Nucl. Phys. A298, 452 (1978)]:.

The result of this change from p to A will be called **quark shadowing**.

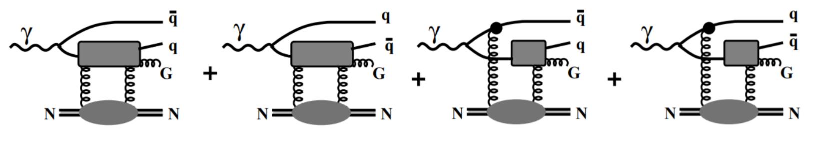
ρ nuclear photoproduction with Glauber–Gribov approach



The Glauber–Gribov approach with the dipole model **is not good enough** to describe the available $\rho(1S)$ photoproduction data.

$|q\bar{q}g\rangle$ fluctuations

In the high energy limit, besides the $|q\bar{q}\rangle$, we need to consider that the photon can split into higher states like $|q\bar{q}g\rangle$, $|q\bar{q}gg\rangle$, ..



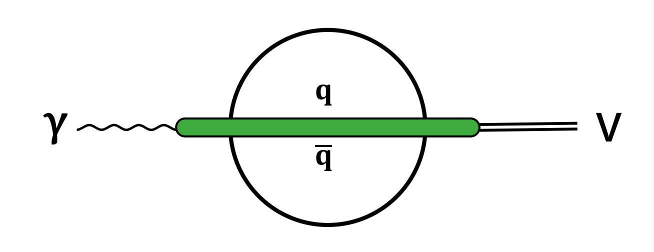
[Kopeliovich, Schafer and Tarasov, Phys. Rev. D 62 054022, 2000]

The proton–dipole cross section takes these soft gluon radiations into account effectively through the fit at LO.

The $q\bar{q}$ fluctuation lifetime, or the coherence length, in photoproduction, is given by the photon energy and the vector meson mass:

$$l_c = \frac{2\omega'}{M_V^2}\,, \tag{1}$$

The color dipole model assumes that the coherence length is bigger than the target radius (i.e., limit of infinite lifetime)



For proton target, this is usually the case.

Coherence length

In nucleus target, the infinite lifetime approximation fails for higher Fock states.

	$\langle l_c \rangle$ [fm]
$\bar{Q}Q$	120.0
$\bar{Q}Qg$	14.2
$\bar{Q}Q2g$	4.2
$\bar{Q}Q3g$	1.9
$\bar{Q}Q4g$	1.1

Nemchik and Kopeliovich, arXiv:2211.16271, for J/ψ (smaller coherence length than light vector meson.

So what we see is that higher Fock states contribute in the proton case but maybe do not fully contribute in the nucleus case.

This implies a reduction of the γA cross section, an effect called **gluon shadowing**.

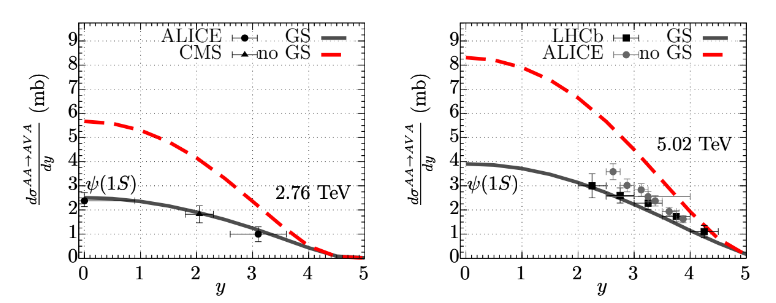
Nemchik and Kopeliovich argue that the Balitsky-Kovchegov (BK) equation considers that all Fock states are frozen during the propagation through the nucleus, which results in a wrong shadowing.

Effective gluon shadowing

The effective gluon shadowing multiplies the proton dipole cross section

$$\sigma_{q\bar{q}} \Rightarrow \sigma_{q\bar{q}} R_g(x, \mu^2)\,.$$

For heavy vector mesons, we used the R_g from EPPS16 with $\mu = M_V/2$
[Henkels, E.G.O., Pasechnik, Trebien, Phys. Rev. D 102, 014024 (2020)].



Light vector mesons: PROBLEM

EPPS and other nuclear distributions are extracted mainly from F_2 data using DGLAP evolution.

The evolution does not reach the light vector meson scale of ρ, ω, and ϕ states.

Also, the gluon shadowing theoretically calculated by Nemchik and Krelina [Eur.Phys.J.Plus 135 (2020) 6, 444], with the same dipole formalism.

By considering only the $Q\bar{Q}g$ fluctuation, their calculation only works for higher Q^2 scale.

We do not have shadowing for smaller scales and this is a PROBLEM.

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We do not have shadowing for smaller scales and this is a PROBLEM.

SOLUTION: Extract the gluon shadowing from the nuclear DIS

$$R^A = \frac{F_2^A}{AF_2^p},$$

Since the dipole cross sections $\sigma_{q\bar{q}}$ is valid for small scales, we can use it to extract the gluon shadowing factor R_g from any available data.

The number of gluons in the fluctuations does not matter in the extration.

F_2 calculations

$$R^A = \frac{F_2^A}{AF_2^p} = R_g - hR_g^2$$

$$h = \Bigg\{ 3\alpha_{em} \sum_{f=1}^{N_f} Z_f^2 Re \int d^2b \int_{-\infty}^{\infty} dz_1 \int_{z_1}^{\infty} dz_2 \int_0^1 d\beta \int d^2 r_2 \int d^2 r_1 \rho(b, z_1)\rho(b, z_2)$$
$$\times\, \sigma_{q\bar{q}}(r_2, x)\sigma_{q\bar{q}}(r_1, x) G_{q\bar{q}}(\mathrm{r}2, z_2; \mathrm{r}1, z_1) \big\{ \left[\beta^2 + (1-\beta)^2\right] \Phi_1(\epsilon, r_2, \lambda)\Phi_1(\epsilon, r_1, \lambda)$$
$$+ \left[m_f^2 + 4Q^2\beta^2(1-\beta)^2\right] \Phi_0(\epsilon, r_2, \lambda)\Phi_0(\epsilon, r_1, \lambda) \big\} \Bigg\} \Bigg/ \Bigg\{ \int d^2 r \int_0^1 d\beta 2N_c\alpha_{em}$$
$$\times \sum_{f=1}^{N_f} Z_f^2 \left[\left(m_f^2 + 4Q^2\beta^2(1-\beta)^2 \right) \Phi_0^2(\epsilon, r, \lambda) + \left(\beta^2(1-\beta)^2 \right) \Phi_1^2(\epsilon, r, \lambda) \right] \Bigg\}$$

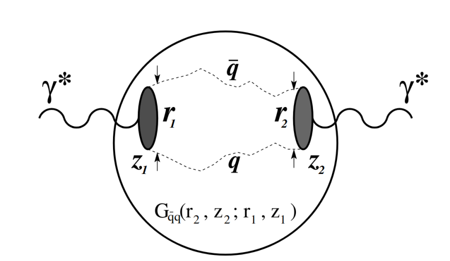
$$\Phi_0(\epsilon, r, \lambda) = \frac{1}{4\pi} \int_0^\infty dt\, \frac{\lambda}{\mathrm{sh}(\lambda t)} \exp\left[-\frac{\lambda\epsilon^2 r^2}{4} \mathrm{cth}(\lambda t) - t \right] ,$$

$$\vec{\Phi}_1(\epsilon, r, \lambda) = \frac{\epsilon^2 \vec{r}}{8\pi} \int_0^\infty dt \left[\frac{\lambda}{\mathrm{sh}(\lambda t)} \right]^2 \exp\left[-\frac{\lambda\epsilon^2 r^2}{4} \mathrm{cth}(\lambda t) - t \right] .$$

Green Function

$$G_{q\bar{q}}(\vec{r_2}, z_2; \vec{r_1}, z_1) = \frac{a^2(\beta)}{2\pi i \sin(\omega\,\Delta z)} \exp\left\{ \frac{i\,a^2(\beta)}{\sin(\omega\,\Delta z)} \left[(r_1^2 + r_2^2)\cos(\omega\,\Delta z) - 2\,\vec{r_1}\cdot\vec{r_2} \right] \right\}$$
$$\times \exp\left[-\frac{i\,\epsilon^2\,\Delta z}{2\,\nu\,\beta\,(1-\beta)} \right] ,$$

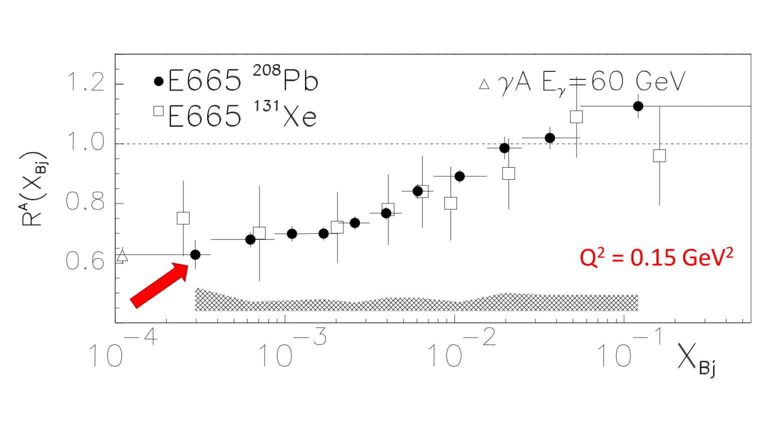
where $\Delta z = z_2 - z_1$, $\lambda = 2\,a^2(\beta)/\epsilon^2$, and $\omega = \frac{a^2(\beta)}{\nu\ \beta(1-\beta)}$ are adjusted to the data on the total photoabsorption cross section, diffractive proton dissociation and shadowing in nuclear photoabsorption reaction [Kopeliovich, Schafer, and Tarasov, Phys.Rev.D 62 (2000) 054022].



[Raufeisen, Tarasov, and Voskresenskaya, Eur.Phys.J.A 5 (1999) 173-182.]

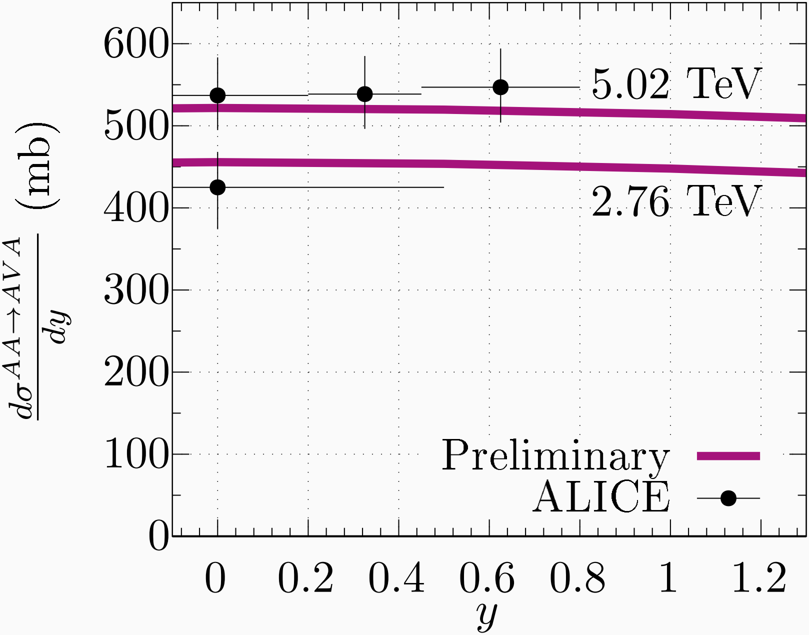
SOLUTION: Extract the gluon shadowing from the nuclear DIS

For our fortune, luck is on our side, and there exists datapoints measured at a low scale for F_2 nuclear structure function in DIS.



Data taken from the Fermilab E665 Collaboration, Z.Phys.C 67 (1995) 403-410.

ρ nuclear photoproduction – with gluon shadowing – preliminary results



Conclusion

- Light vector meson photoproduction is a process with small hard scales Q^2.
- Available data of light vector meson photoproduction in γp collisions is well described by the dipole model.
- The ratio between excited and ground states provides important information about the meson wavefunction and the color dipole cross section.
- In the nuclear target case, the shadowing is necessary and can be extracted from F_2 measurements.
- It looks like the few available nuclear datapoints on photoproduction are well described by our calculation.

Thank you!